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Title: **Ultrasonic NDE Simulation for Composite Manufacturing Defects**

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ABSTRACT

The increased use of composites in aerospace components is expected to continue into the future. The large scale use of composites in aerospace necessitates the development of composite-appropriate nondestructive evaluation (NDE) methods to quantitatively characterize defects in as-manufactured parts and damage incurred during or post manufacturing. Ultrasonic techniques are one of the most common approaches for defect/damage detection in composite materials. One key technical challenge area included in NASA's Advanced Composite's Project is to develop optimized rapid inspection methods for composite materials. Common manufacturing defects in carbon fiber reinforced polymer (CFRP) composites include fiber waviness (in-plane and out-of-plane), porosity, and disbonds; among others. This paper is an overview of ongoing work to develop ultrasonic wavefield based methods for characterizing manufacturing waviness defects. The paper describes the development and implementation of a custom ultrasound simulation tool that is used to model ultrasonic wave interaction with in-plane fiber waviness (also known as marcelling). Wavefield data processing methods are applied to the simulation data to explore possible routes for quantitative defect characterization.

INTRODUCTION

The aerospace industry continues to expand use of composite materials to in order to enable lightweight advanced aircraft and spacecraft designs. However, there is currently a decade long timeline for developing and certifying composite structures for use by industry and government [1]. NASA's Advanced Composites Project has the goal of reducing the timeline for certification of composite materials and structures [2]. A key technical area which affects composite certification is inspection. Rapid nondestructive evaluation (NDE) techniques are needed to quantify and characterize defects/damage in aerospace composites. Manufacturing defects in carbon fiber reinforced polymer (CFRP) composites include fiber waviness (in-plane/marcelling and out-of-plane/wrinkling), fiber misalignment, porosity, foreign object damage (FOD), and disbonds. Such defects can reduce the strength of the material and thus negatively affect the reliability and durability of composite parts [3, 4]. For the two categories of fiber waviness defects (in-plane and out-of-plane), both can be induced during curing due to temperature gradients [5]. Wrinkling can also be created during layup of complex geometry parts. Additionally, it has been reported that wrinkling can be converted to in-plane waviness during the curing process [6]. Studies of wrinkling appear to be more prevalent in the literature than studies on in-plane waviness. In this regard, it is noted that wrinkling defects are more readily visible to the human eye and therefore may be more easily observed as an issue in composite manufacturing.

Ultrasonic inspection is one of the most commonly used NDE techniques for detection and quantification of damage in composites. Currently, many researchers are investigating the use of ultrasonic guided waves (GW) for large area inspection of composites. Prior work reported in the literature focuses on GW approaches for detecting and quantifying damage in composites using one of two approaches: 1) the use of multiple contact sensors for sending and receiving ultrasonic wave data, 2) the use of a single contact sensor or noncontact methods for ultrasound excitation coupled with wavefield measurement via noncontact laser Doppler vibrometry (LDV). With respect to the former, prior publications in the literature present methodologies for tomography, phased array, or sparse array setups with the associated data processing approaches [7-9]. The second approach entails measurement of the GW wavefield data using point-by-point LDV scanning combined with data processing methods such as instantaneous or local wavenumber technique [10, 11]. Methods for reducing the time required for wavefield scanning, enabling more rapid inspection, have also been reported [12-14]. Much of the prior work listed above focuses on detection of delamination and disbond type defects in composites.

The work presented in this paper is focused on the study of GW interaction with in-plane fiber waviness. Preliminary investigations reported in prior literature have found that GWs are affected by fiber waviness [15]. This defect type can be especially difficult to detect since it is not readily visible to the eye and can occur interior to the composite while causing no surface indication. For manufacturing defects such as this, it is challenging to create representative NDE standards for experimental testing. Simulation tools are therefore particularly useful in guiding the development of detection and quantification techniques. In this work elastodynamic finite integration technique (EFIT) has been implemented to simulate wave interaction with fiber waviness. The following section describes the simulation approached used for waviness. Studies of wave interaction are then described, followed by a conclusion.

ULTRASOUND SIMULATION FOR FIBER WAVINESS IN COMPOSITES

Numerous mathematical approaches, both analytical and numerical, have been reported for modeling and simulation of ultrasonic wave propagation in elastic materials. Analytical methods are limited in the types of cases they can accurately represent [13]. Numerical methods are relied on in cases with complex damage geometries, complex specimen geometry/structure and/or non-isotropic material properties. Common numerical methods include finite element analysis (FEA), finite difference (FD), and finite integration technique (FIT). Elastodynamic finite integration technique (EFIT) is a numerical method similar to staggered-grid finite difference techniques. The technique has been in use since the early 1990s with extensive foundational work reported by authors such as Fellingner, Marklein, and Schubert, among others [16-20].

EFIT is implemented to study wave interaction with fiber waviness defects. The equations are derived in Cartesian coordinates and the simulation uses a square discretized grid for calculating the stresses and velocities at all spatial points in the 3-dimensional (3D) simulation. The code is parallelized to run efficiently on cluster or multicore computing resources using Message Passing Interface (MPI). Code validation studies and additional discussion about EFIT for composites can be found in prior work by the authors [21].

In-Plane Fiber Waviness

For a pristine CFRP laminate the EFIT code can account for the anisotropic material properties of each individual ply layer by including appropriate stiffness matrices for each ply rotation. In addition, the custom simulation code allows direct control over the stiffness matrix at every grid point in the 3D simulation space. The incorporation of in-plane waviness (marcelling) is therefore implemented using the appropriately rotated stiffness matrix at each grid point location corresponding to fiber waviness (see Figure 1).

In the most general description, waviness is described by a function, $f(x, y, z)$ which depends on spatial location in x, y, z . For the cases studied in this paper, it was assumed that in the wavy fibers follow the same functional form in the y direction, i.e., waviness becomes a function of only x and z , $f(x, z)$. For each z location (depth) the tangent to the curve is found and the corresponding rotation angle is defined as:

$$\theta_{x,z} = \tan^{-1} \left(\frac{f(x_2,z) - f(x_1,z)}{(x_2 - x_1)} \right) \quad (1)$$

where the 0 degree fiber direction is taken as $\theta_{x,z} = 0$. The stiffness matrix is rotated by the appropriate $\theta_{x,z}$ for each grid point in the ultrasound simulation. Prior publications in the literature were used to define a degree of fiber waviness that is relevant for CFRP composites. The amount of fiber waviness in a CFRP can be defined by the amplitude of the fiber wave and the associated wavelength.

Various authors have studied fiber waviness in CFRP composites. Mizukami recently reported eddy current based detection of CFRP fiber waviness. For those studies representative waviness samples were created where the level of waviness was measured at an amplitude of $A = 1.1$ mm over a wavelength of $\lambda = 15.9$ mm [5].

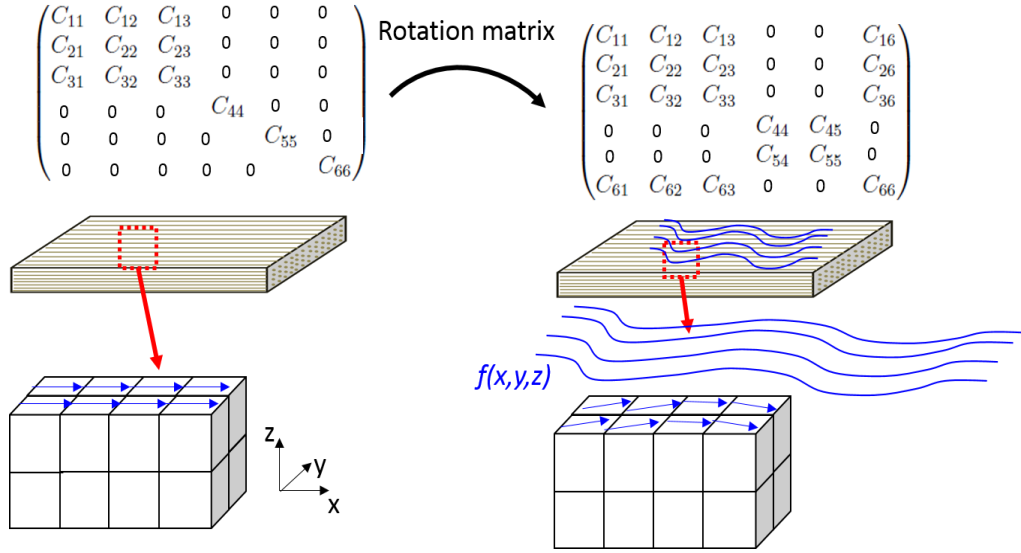


Figure 1. Diagram of process for calculating the angle of in-plane fiber waviness to be included in the custom ultrasound simulation. Waviness in the most general sense is defined by a function $f(x, z)$. In this paper, for each simulation grid location the stiffness matrix is rotated according to equation (1).

Fuhr and colleagues studied in-plane waviness (for automotive composites) and reported degrees of waviness ranging from $A=0.6$ mm $\lambda=20$ mm to $A=1.5$ mm $\lambda=10$ mm [22]. Fuhr's work found that increased amplitude leads to decreases in stiffness and strength.

For the studies presented in this paper the fiber waviness was defined with $A=2$ mm and $\lambda=16$ mm in the functional form of a 2-cycle cosine wave. The fiber waviness was included in only the top ply of the CFRP laminate. As stated above, this waviness was incorporated into the simulation by specifying the appropriately rotated stiffness matrix for all points in the wavy region. Figure 2 shows the θ rotation angle with respect to location for a simulation of a simple unidirectional CFRP laminate containing waviness in the top ply layer.

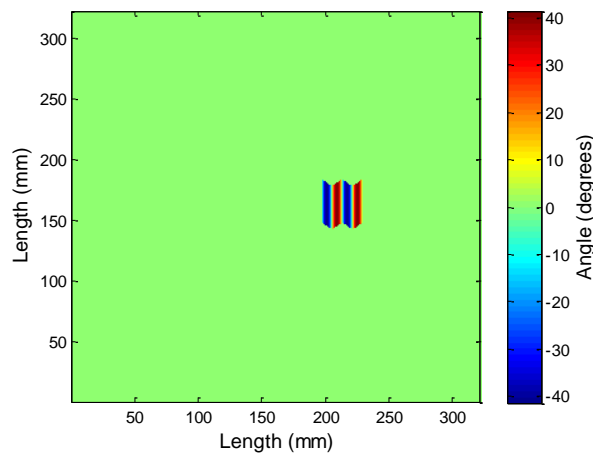


Figure 2. Angle of stiffness matrix rotation as a function of x and y spatial location, for a simulation case of a unidirectional CFRP laminate containing a region of waviness in the top ply layer.

Simulation Cases and Wavefield Results

Two cases were simulated for the preliminary studies presented in this paper. Both cases are for laminates made up of IM7/8552 unidirectional prepreg [21]. The first, and most simple case, corresponds to a unidirectional 8-ply thick CFRP laminate with waviness specified as shown in Figure 2. A 6.5-cycle 200kHz Hann windowed sine wave was used as the excitation signal in the simulation. Two guided waves, S_0 and A_0 , exist at this frequency-thickness. Figure 3 shows a single snapshot in time of the out-of-plane velocity at the ‘top’ surface (uppermost top ply containing waviness) and on the ‘back’ surface (opposite to the side with ply waviness) of the laminate. At this point in time the S_0 mode has interacted with the wavy region (visible as ripples inside the red box in Figure 3). The colormap in the figures represents amplitude, and has been

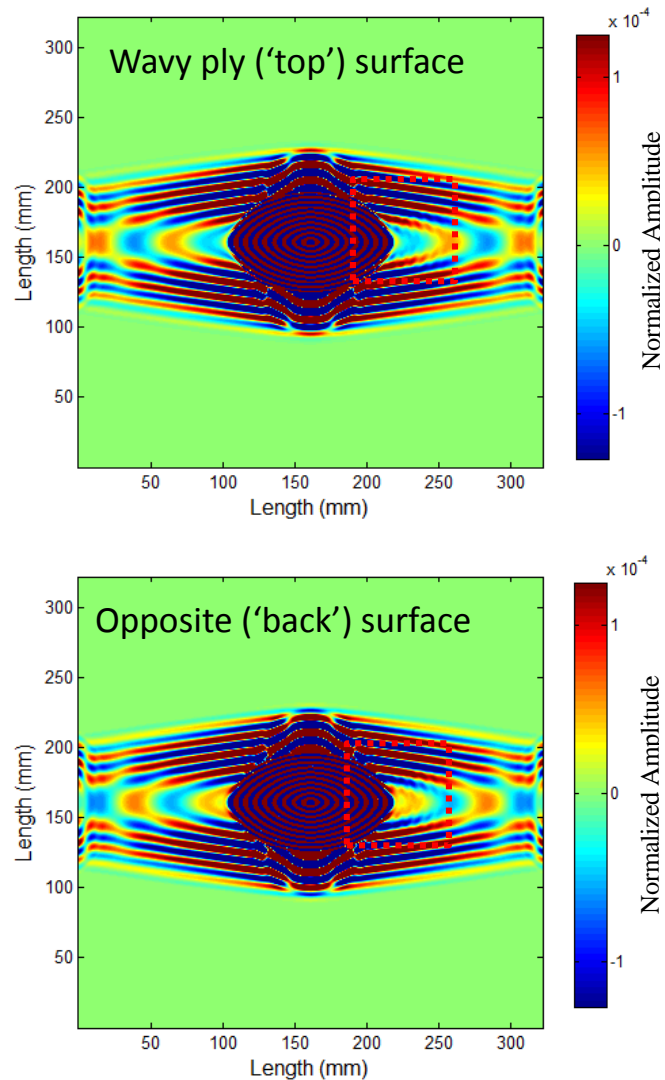


Figure 3. Simulated wavefield data at a single point in time for unidirectional laminate; showing out-of-plane velocity on the ‘top’ surface (uppermost top ply containing waviness) and on the ‘back’ surface (opposite to the side with ply waviness). The red dashed box surrounds the waviness region (and is larger than the wavy region). The excitation (transducer) location is in the center of the space.

saturated to show the effects of wave interaction with the fiber waviness (the red dashed box is placed surrounding the region of waviness). The wavefields shown in Figure 3 demonstrate that waviness on one surface of the 8-ply unidirectional CFRP affects the guided waves throughout the thickness of the laminate (since the effects are also visible on the surface opposite the wavy region).

A second case was implemented for an 8-ply thick crossply laminate of layup $[0/90/0/90]_s$ containing waviness as shown in Figure 2 in the uppermost (top) ply. Again, two guided wave modes exist for this frequency-thickness. For this case the effect of wave interaction with the S_0 mode was much less visible than for the unidirectional case. However, at a later point in time reflections of the A_0 mode from the wavy region are visible (traveling to the left in the center of Figure 4). In addition, as in the unidirectional case, the effects of the wavy region were again observed on the opposite ('back') surface.

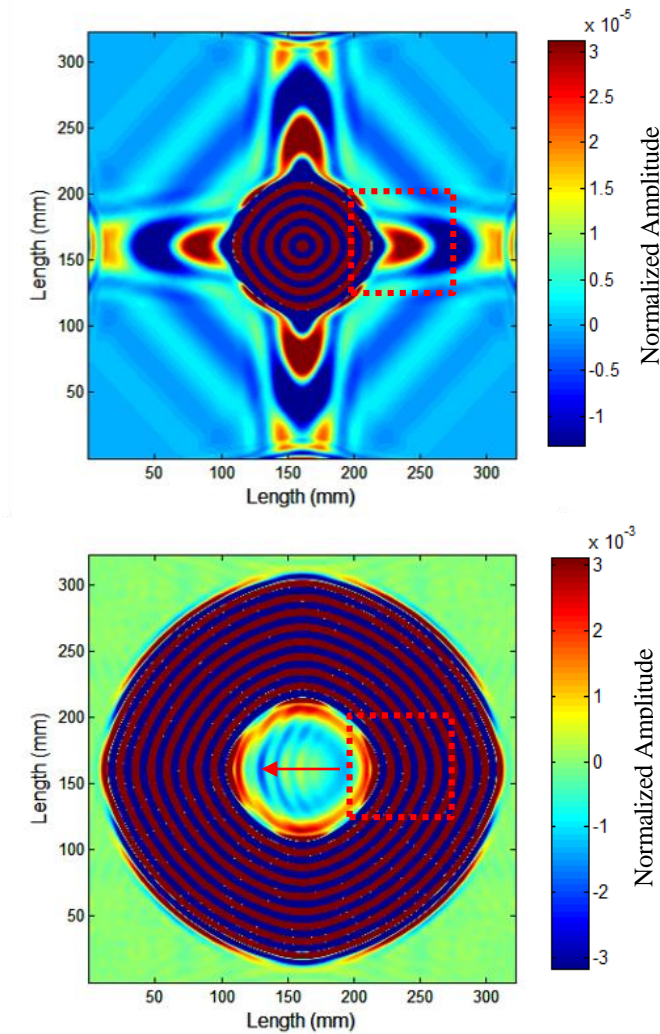


Figure 4. Simulated wavefield data at two points in time for the crossply laminate (top earlier point in time than bottom image). Plots show out-of-plane velocity on the 'top' surface (uppermost top ply containing waviness). The colormap in the figures is saturated to show wave effects due to waviness. In the bottom image reflections traveling left from the wavy region are denoted by the red arrow. Again, the general waviness region is indicated by the red dashed box.

Wavefield Processing

Prior work in the field, including work by the authors, has demonstrated that wavenumber based guided wavefield processing methods can yield quantitative information about CFRP defects such as delaminations [23, 24]. In a CFRP containing delamination damage, guided waves will change wavenumber above/below delamination regions. However, for defects such as in-plane waviness it is expected that the impact on wavenumber may be much less significant. To assess the appropriateness of applying wavenumber based analysis to fiber-waviness data, basic 2D wavenumber calculations have been performed for the two simulation cases. Figure 5 shows the kx versus ky wavenumber plots from the out-of-plane velocity wavefield of the unidirectional and crossply cases. The figures show the resulting A_0 wavenumber distribution for the pristine case of each layup (i.e., no waviness), the layup with waviness as defined in figure 2, and the wavenumber plot when the pristine case is subtracted from the wavy case.

The plots show that no new wavenumbers are created by the presence of waviness (as occurs in cases with delamination damage). Yet, indications are observed in the difference plots that represent the presence of changes in directional amplitude in wavenumber due to the wavy region. This results means that it may be possible to apply some type of wavenumber based post-processing to quantify waviness. However, further study is needed to confirm whether wavenumber analysis is useful in such cases (especially since ‘pristine case’ subtraction is not realistic in a non-laboratory setting).

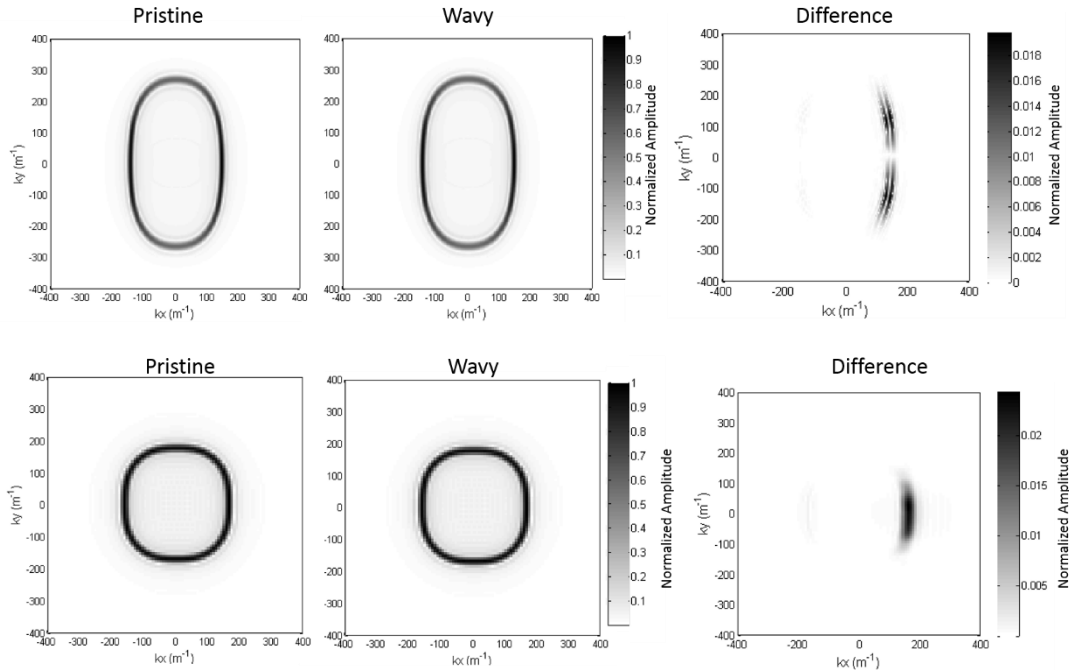


Figure 5. 2D Wavenumber plots (kx versus ky). Top: pristine unidirectional case (left), unidirectional case containing waviness (middle), and the difference between the two wavenumber plots (right). Bottom: pristine crossply case (left), crossply case containing waviness (middle), and the difference between the two wavenumber plots (right).

CONCLUSION

Validated simulation tools, such as the custom code used in this study, can be used to inform and optimize inspection methods. The preliminary case studies presented in this paper demonstrate the usefulness of simulation tools for investigating and understanding the effects of composite manufacturing defects on ultrasonic waves. It was shown that for thin CFRP laminates, waviness over even a small region can affect guided ultrasonic waves throughout the thickness of the laminate. Therefore, guided wave analysis may yield information about waviness within a laminate or on the opposite surface from where an inspection occurs. Further studies are needed to assess the impact of varying degrees of in-plane waviness on guided ultrasonic waves. Factors such as the depth at which waviness occurs, the amplitude and wavelength of waviness, the size of region over which it occurs, and the layout in which it occurs should all be investigated further. Simulation data for a variety of cases can enable cost-effective investigation of inspection methodologies and post-processing approaches for quantifying waviness. Experimental investigations can then be performed utilizing defect quantification methods identified as the most promising.

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